MONTICELLO FIELD LYSIMETRY: DESIGN AND MONITORING OF AN ALTERNATIVE COVER

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ABSTRACT

The U.S. Department of Energy (DOE) Grand Junction Office (GJO) conducted a series of field lysimeter experiments to help design and then monitor the performance of an engineered cover for a uranium mill tailings disposal cell at the Monticello, Utah, Superfund site. The U.S. Environmental Protection Agency (EPA), the State of Utah Department of Environmental Quality, and the DOE Office of Science and Technology collaborated with GJO on the project. The lysimeter test facility evolved as a sequence of installations, first to test the concept of using an evapotranspiration cover design at Monticello, next to evaluate the soil-water balance of the final engineered design, and finally to monitor the hydrologic performance of a large facet of the completed disposal cell cover. In 1990, GJO installed small weighing lysimeters containing intact, 100-cm-deep profiles of undisturbed silt loam soil (monoliths) overlying a pea-gravel capillary barrier and supporting mature native grasses. We compared leaf water potential and leaf transpiration of plants on and adjacent to the lysimeters to test effects of the small weighing lysimeter design on plant behavior. Because of favorable monolith lysimeter results, we constructed an array of 15 additional small weighing lysimeters in 1993 to test the effects of varying soil types and soil layer thickness on soil-water balance and water-storage capacity. In 1998 and 1999, GJO teamed with EPA Region 8 on the construction of large caisson lysimeters to evaluate the water balance of the final cover design for the Monticello disposal cell. The cover layer sequence constructed inside the caissons matched as-built engineering parameters for the actual cover. In 2000, GJO and the EPA Alternative Cover Assessment Program collaborated on a large drainage lysimeter constructed to monitor the water balance of a 3-ha facet of the 14-ha disposal cell cover at Monticello.

INTRODUCTION

The Monticello, Utah, mill, built in 1942 to provide vanadium for World War II and later modified to process uranium ore, produced more than 2.5 million m^3 of tailings until its closure in the early 1960s. The U.S. Department of Energy (DOE) Grand Junction Office (GJO), Region 8 of the U.S. Environmental Protection Agency (EPA), and the State of Utah Department of Environmental Quality collaborated in the recent construction of a disposal cell to contain tailings and tailings-contaminated materials at Monticello. Remedial actions were regulated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). GJO faced unprecedented regulatory requirements in achieving the accepted remedial actions for the site. The disposal cell design was required to satisfy both minimum technology guidance for hazardous waste disposal facilities (1) under subtitle C of the Resource Conservation and Recovery Act of 1976 (RCRA) and design guidance for radon attenuation and 1,000-year longevity (2) under the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA). The GJO needed a design that would control migration of subsurface contaminants for hundreds of years and would continue to do so while natural processes act to mobilize contaminants.

Early cover designs constructed for UMTRCA disposal cells typically consisted of compacted soil layers (CSLs), sand drains, and rock riprap intended to function as physical barriers to radon releases, water infiltration, and erosion.(2, 3) Typical RCRA cover designs also consist of prescribed physical barriers.(1) Such conventional engineering design approaches overlook many natural processes that can degrade physical barriers. After only a few years, CSLs have desiccated and cracked under routine wetting and drying conditions (4, 5), and biological disturbances threaten cover integrity at many sites.(6, 7, 8, 9, 10) GJO's goal at Monticello was to design an engineered cover system that focused on enhancing beneficial natural processes that may improve containment in the long term, rather than barriers to natural processes that would degrade in the long term.(11)

At semiarid sites such as Monticello, relatively low precipitation (P), high potential evapotranspiration (PET), and thick unsaturated soils seem to favor long-term hydrologic isolation of buried waste.(12, 13, 14, 15) But simple P/PET relationships inadequately predict recharge in arid regions that can approach 50% of precipitation in coarse-textured soils denuded of vegetation.(16) At arid and semiarid waste disposal sites, recharge can be minimized by using thick, fine-textured soil covers that store precipitation in the root zone where it is seasonally removed by evapotranspiration (ET).(17, 18, 19, 20, 21, 22, 23) To be accepted by regulators, end users must demonstrate that the water balance of these *alternative* cover designs is at least equivalent to conventional designs.

Weighing and drainage lysimeters offer the most direct and reliable means for evaluating soil-water balance of alternative cover designs.(24) Lysimeters have been used for many years to evaluate irrigation needs (25, 26) and have more recently been used to test the hydrologic performance of waste landfill cover designs.(27, 28, 29, 30) GJO and its partners conducted a series of field lysimeter experiments beginning in 1990 to help design and then monitor the performance of a disposal cell cover design at Monticello that would rely in part on a high soil water-storage capacity and high ET to limit infiltration of water and leaching of tailings. The lysimeter test facility evolved as a sequence of installations, first to test the ET cover design concept at Monticello, next to evaluate the soil-water balance of the final engineered design, and finally to monitor the hydrologic performance of a large facet of the completed disposal cell cover. This paper presents a review of the status of field lysimeter studies at Monticello.

STUDY AREA

The study area is adjacent to the tailings disposal cell 2 km south of Monticello, Utah. Monticello is semiarid with cold, windy winters and mild summers. The 30-yr average (1961–1990) annual precipitation is 39 cm. The average minimum January temperature is –10.5 °C and the average July maximum temperature is 28.9 °C. The year can be characterized as three seasons with respect to soil-water balance: November through March (average precipitation equals 16 cm) is the season of deep infiltration and moisture accumulation in soils; April through June (average precipitation equals 6 cm) is a moisture-depletion period when plants become water stressed; and July through October (average precipitation equals 17 cm) is a season of variable shallow moisture accumulation and depletion resulting from monsoonal convection storms. Annual snowfall averages 160 to 170 cm.

Soils in the region range from silt loam to sandy clay loam formed in Pleistocene loess.(31) The natural vegetation at the disposal cell site consists primarily of Western wheatgrass (*Pascopyrum smithii* [Rydb.] Á. Löve), Sandberg bluegrass (*Poa secunda* J. Presl), blue grama (*Bouteloua gracilis* [Kunth] Lag.), mountain big sagebrush (*Artemisia tridentata* Nutt. subsp. *vaseyana* [Rydb.] Beetle), and gray rabbitbrush (*Chrysothamnus nauseosus* [Pall. ex Pursh] Britton) with a canopy coverage of 50% to 60% as measured using a point-intercept method.(32) The monolith lysimeters were constructed in a near monoculture of *P. smithii* adjacent to the construction site for the uranium mill tailings disposal cell.

SMALL WEIGHING LYSIMETERS

Our premise for this study is that small weighing lysimeters can offer adequate accuracy and precision, can provide a means for replication in expanded experimental designs, and can be inexpensively installed and operated at remote sites. The dual purposes of the study were to evaluate how effectively plant water relations in small lysimeters represent undisturbed conditions and, therefore, their adequacy for screening tests of the water balance of engineered cover designs and to measure the soil-water balance of simple ET cover designs for the Monticello disposal cell. Soil monoliths were used to evaluate the adequacy of the small lysimeters, and an array of 15 small weighing lysimeters was installed to compare different engineered cover designs.

Small weighing lysimeters have previously been used for agronomic applications (33, 34, 35, 36), to study contaminant transport (37, 38), and to test effects of various erosion control practices on soil-water balance.(29, 39) Potential drawbacks of small weighing lysimeters include restriction of rooting volume, accentuation of diurnal temperature fluctuations, insufficient volume to adequately encompass soil macropore variability, creation of an artificial lower boundary in the soil profile, and greater edge flow effects.(40, 41, 42)

Plant Water Relations Study

We installed small monolith lysimeters to test the hypothesis that plant water relations inside the lysimeters and in adjacent undisturbed areas are the same. Five lysimeters were constructed at the site during October and November 1991. Each lysimeter consisted of a 102-cm length of 30-cm inside diameter (i.d.) polyvinyl chloride (PVC) pipe fitted with lifting rings at the top of the pipe and a PVC end cap with a drainage port at the bottom of the pipe. The two lifting rings consisted of three-hole gate hinges bolted flush to the upper outside edge of the lysimeter pipe. A sloping PVC plate that was heat welded in the bottom of the end caps directed drainage water to a drainage port. Clear, flexible polymer tubes were attached with threaded fittings to the drainage ports to function as collection reservoirs. The lysimeters were also designed to be coupled to a plant gas-exchange chamber for direct measurement of ET and photosynthesis.(43, 44)

Lysimeter Installation and Plant Water Status Measurement Methods

Installation of monolith lysimeters involved excavating an intact soil pedestal slightly greater in diameter and height than the lysimeter pipe, fitting the pipe down over the pedestal, detaching this encased soil monolith, placing pea gravel and a geofabric separator in the end cap, sealing the end cap to the bottom of the pipe, and then lowering the complete lysimeter into a 38-cm (i.d.) PVC sleeve that had been placed in the original excavation. A tight fit of the soil pedestal within the PVC pipe was achieved by beveling the lower edge of the pipe and wetting the outside surface of the soil pedestal. Tops of the lysimeters were installed slightly above grade to prevent run-on. Locations were chosen within a *P. smithii* stand growing in a thick clay loam loess. The soil monolith lysimeters preserved, as well as possible, the native soil structure and plant root distribution.

We randomly sampled *P. smithii* plants growing on and adjacent to the lysimeters to evaluate the effects of isolating a soil monolith on plant water status. Predawn leaf water potential (ψ_l) values of green culms were measured monthly during the growing season using a pressure chamber technique.(45) Diurnal patterns of stomatal conductance and transpiration were measured in early July, when soil water content and ψ_l values were lowest, using a Li-Cor, Inc., LI-1600 steady-state porometer. Data were collected from random clumps of *P. smithii* leaves growing on and adjacent to all five lysimeters. Enough leaf material was enclosed in the porometer cuvette to achieve a null balance at ambient relative humidity. Single-sided leaf area was estimated from width and length measurements of leaf sections enclosed in the cuvette. Air temperature, photosynthetic photon flux density, and relative humidity were also measured concurrently with the porometer. A double sampling approach was used to estimate single-side leaf area. Plant (culm) height, leaf number, leaf length, and leaf width were measured in 10 randomly located, 30-cm-diameter quadrats adjacent to the lysimeters. All plants in the quadrat were clipped and their leaf areas were measured using a Li-Cor Inc., LI-COR 3100 area meter. Leaf area was estimated from regressions against dimensions of plants measured on the lysimeters. Data are presented as means plus or minus the standard error of the mean unless stated otherwise.

Leaf Water Potential

Pre-dawn ψ_l values for *P. smithii* growing on and adjacent to the lysimeters were similar early in the growing season, diverged significantly during the mid-summer moisture depletion period, and then reconverged following the late-summer monsoons (Figure 1). During 1991, matching predawn tension values on and adjacent to lysimeters rose slightly between May 2 and June 5. By July 1, the on-lysimeter ψ_x values (–2.8 ± 0.1) were 1.7 MPa lower than adjacent-to lysimeter values. This significant difference continued through July and into August. By September 13, after a period of late summer rains, ψ_l values for *P. smithii* growing on lysimeters were again not significantly different from the surrounding population.

Divergence of predawn ψ_l values for *P. smithii* on and adjacent to the lysimeters came later and was less pronounced in 1993, even though overall rates and magnitudes of change were greater (Figure 1). With the extremely wet winter and month of May, 1993 ψ_l values remained close to zero until after June 1. By the end of June, ψ_l values for *P. smithii* on and adjacent to the lysimeters fell to less than –2.0 MPa. The only significant separation was observed on August 4 when on-lysimeter ψ_l values (–3.5 ± 0.1 MPa) were 1.1 MPa more negative than adjacent-to lysimeter ψ_l values. As in 1991, once the summer monsoons began replenishing soil moisture, ψ_l values converged and rose above –0.5 MPa.

Porometry and Leaf Area

In 1991, the lowest water-storage values and the greatest seasonal divergence in ψ_l values for grasses growing on and adjacent to the lysimeters were observed in early July (Figure 1). July 6 was a warm, partly cloudy day with the vapor pressure deficit (VPD) rising to 34 mb by noon (Figure 2b). Air temperature and vapor pressure deficit on and adjacent to the lysimeters were not significantly different (Figures 2a and 2b, respectively). Predawn ψ_l values for *P. smithii* were –2.9 ± 0.2 MPa on the lysimeters and –1.5 ± 0.2 MPa adjacent to the lysimeters. By 1100 hr, these values had dropped to –4.17 ± 0.3 MPa and –3.10 ± 0.4 MPa, respectively. Stomatal conductance and transpiration rates calculated on a leaf area basis were lower for *P. smithii* growing on the lysimeters throughout the day (Figures 2d and 2e). A drop in both variables at 1300 hr corresponds to partial cloud cover, as indicated by the PAR curves (Figure 2c).

Lower stomatal conductance and transpiration rates of grasses growing in the lysimeters are consistent with ψ_l data. Transpiration from water-stressed *P. smithii* growing on the lysimeters was less than that from the undisturbed population. On the basis of this diurnal data, we infer that transpiration was likely lower on the lysimeters for the entire period between June and late August when ψ_x values diverged below that of the surrounding population (Figure 1). *P. smithii* leaf area adjacent to the lysimeters was 0.0608 ± 0.0052 m^{-2} while leaf area on the lysimeters was 0.0455 ± 0.0029 m^{-2} or 25% lower.

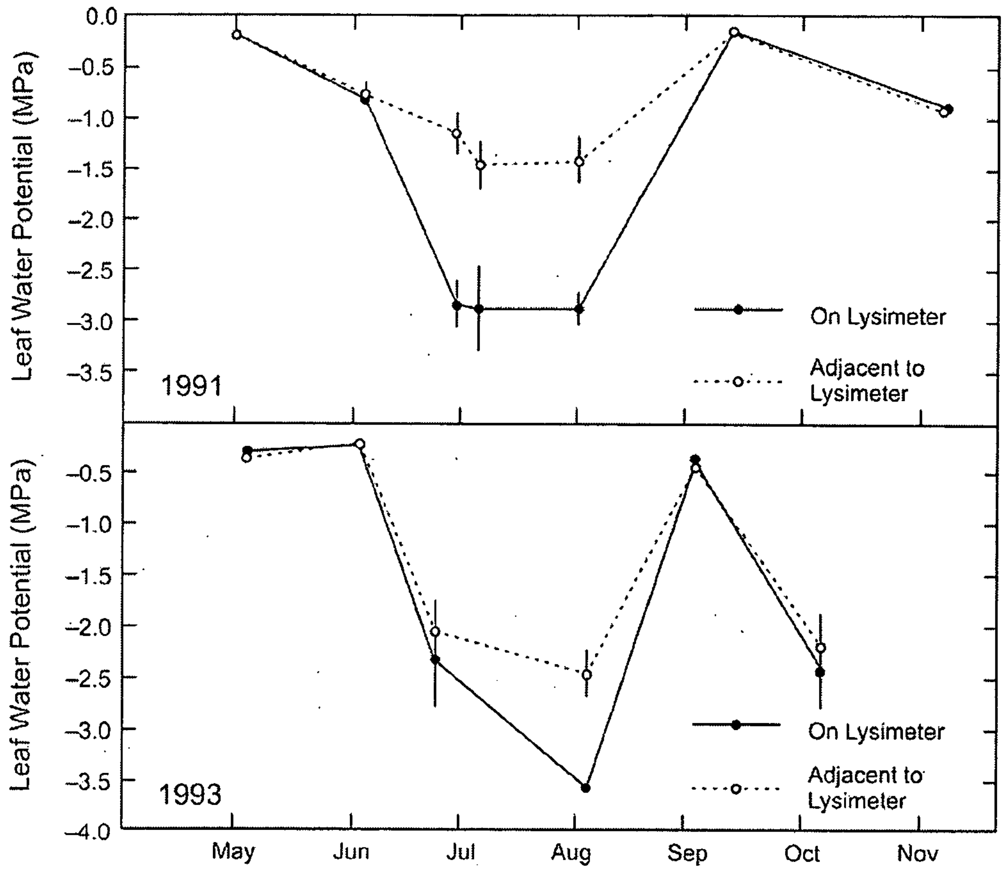

Figure 1. Predawn leaf water potential (ψ_l) values for *P. smithii* growing on and adjacent to the small monolith lysimeters between May and November 1991 and between May and October 1993. Bars are 2 standard error of the mean; $n = 5$.

Discussion

A comparison of plant water relations data in monolith lysimeters and in adjacent undisturbed soils reflects a combination of factors associated with isolating the soil monoliths and has implications for the usefulness of small lysimeters. Confining undisturbed soil profiles and vegetation in the small lysimeters had no observable effect on species composition but did alter *P. smithii* abundance and the seasonality and magnitude of water stress. After more than 3 yr, plant species composition on and adjacent to the lysimeters remained comparable. For example, a dense carpet of *A. tridentata* seedings established in 1991 both on and adjacent to two of the lysimeters. By 1993, only a few *A. tridentata* plants had survived in either location.

The 25% lower leaf area for *P. smithii* on the lysimeters compared with those in the undisturbed area reflects the effect of confining plants in lysimeters during the 3-yr period. *P. smithii* is a rhizomatous grass and cutting the rhizome during lysimeter construction separated ramets within the lysimeter from the rest of the genet outside the lysimeter wall. This separation stopped transfer of photosynthates, nitrogen, water, and hormones from the larger external genet (46) and, therefore, may have caused reduction in leaf area of ramets inside the lysimeter.

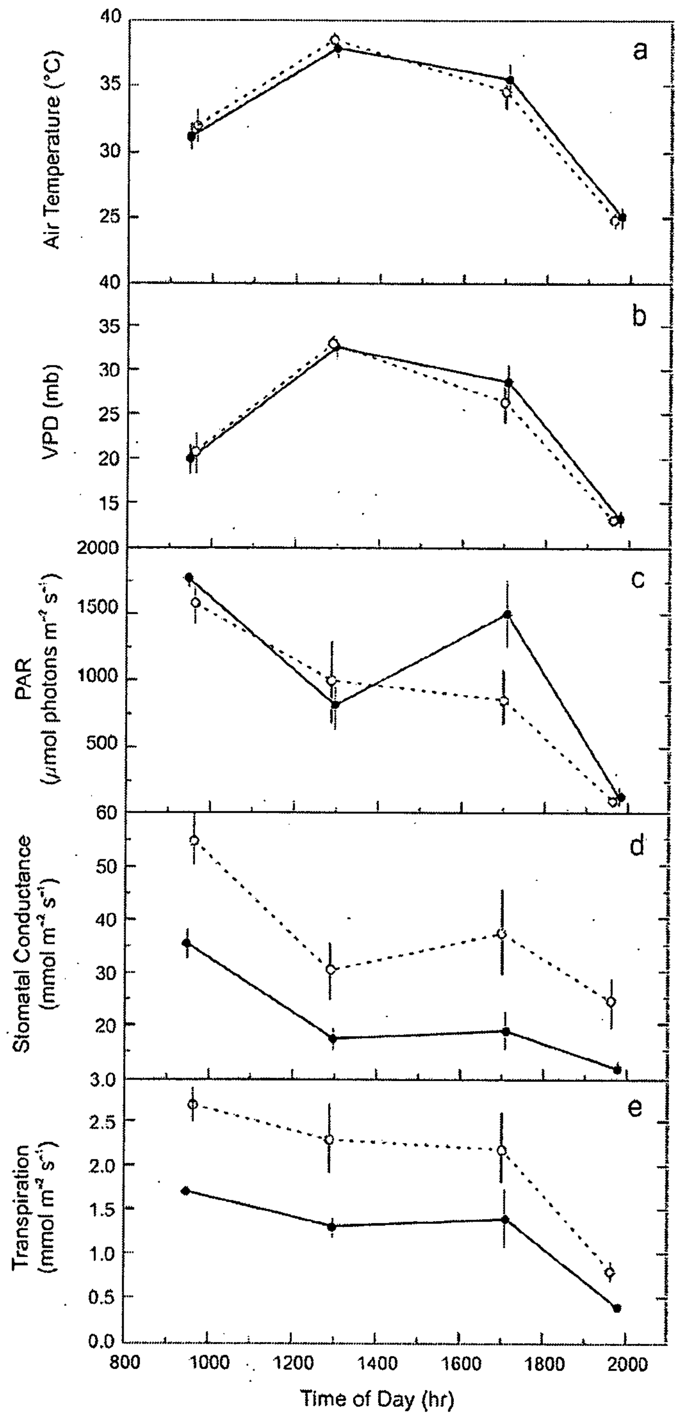

Figure 2. Diurnal porometer responses for *P. smithii* growing on (solid lines) and adjacent to (dashed lines) small monolith lysimeters on July 6, 1991: (a) air temperature, (b) vapor pressure deficit (VPD), (c) photosynthetically active radiation (PAR), (d) stomatal conductance, and (e) transpiration. Bars are 2 standard error of the mean; $n = 5$.

The ψ_l data suggest that this reduction in *P. smithii* leaf area between 1991 and 1993 was an adaptation to greater water stress within lysimeters during the mid-summer season of soil moisture depletion. Small leaf pressure potential differences on compared with adjacent to the lysimeters in 1993 reflect the accommodation of *P. smithii* to drier conditions. In 1993, we measured a lower magnitude and shorter duration of the divergence between ψ_l time series on lysimeters and in undisturbed areas than in 1991. *P. smithii* water stress in 1993 also lagged 1991 values in June, both on and adjacent to the lysimeters, but then became more intense by August. This contrast reflects lower winter and spring precipitation and higher June and July precipitation in 1991. The ψ_l data also indicate that soils in the root zone were drier inside the lysimeters than in adjacent areas. Correlations between predawn ψ_l and soil water potential values have been observed for both C3 and C4 grasses, although the correlation weakens as phenological development becomes more advanced.(47, 48)

Porometry data show that the physiological responses of *P. smithii* to confinement in the lysimeters are related to water stress. *P. smithii* is rhizomatous and the shoots within the lysimeters have been deprived of water from rhizomes and roots of neighboring plants. Lower *P. smithii* stomatal conductance and transpiration rates as measured with the leaf porometer in 1991 are consistent with leaf water potential data. We would expect water-stressed grasses in the lysimeters to transpire less water than grasses in the undisturbed population. We can infer from these diurnal porometry data that transpiration rates continued lower on than adjacent to the lysimeters for the entire period between June and late August 1991 when ψ_l values remained more negative. Predawn ψ_l values can be a strong determinant of conductance and transpiration, independent of other diurnal variables.(48)

Results of the monolith lysimeter tests indicate that our small lysimeters moderately underestimate evapotranspiration and, therefore, would provide a conservative measure of drainage from a soil profile. We conclude that the results support the use of the inexpensive, small lysimeters as a reasonable alternative to large agronomic-type lysimeters for initial screening tests of the hydrologic performance of disposal cell cover designs, particularly for factorial experiments requiring multiple treatments and replication. This conclusion supported our decision to use small lysimeters to test alternative cover designs for the Monticello disposal cell.

Small Lysimeter Array

An array of small lysimeters was installed at Monticello to measure the soil-water balance of alternative cover designs for the disposal cell. The most basic alternative cover design consists of a fine-textured soil layer ("sponge layer") overlying a coarse-textured layer or capillary barrier. Unless the water content of the sponge layer becomes elevated above its storage capacity, in accordance with Richards effect (49), downward water movement should be inconsequential. Water-storage capacity has been defined as the difference between the amount of water retained in a soil at field capacity, the *drained upper limit,* and the amount of water remaining when the soil dries to the permanent wilting point, the *lower limit of extraction.*(50, 51) At the so-called permanent wilting point, soil water tensions become too high for plants to remove any more water. Field capacity is "the amount of water held in a soil after excess water has drained away."(52) Although field capacity is not an intrinsic physical property of soils independent of the way it is measured (53), field capacity has pragmatic importance for quantifying a threshold water content at which drainage from the capillary barrier occurs. The water-storage capacity is increased when a fine-textured soil layer is placed over a coarse-textured layer or a capillary barrier.(54) For our purposes, water-storage capacity is measured as the difference between the drained upper limit and the lower limit of extraction by plants.

Lysimeter Treatment Structure and Facility Design

The treatment structure (Table I) compared three soil types and three soil sponge-layer thicknesses overlying a 15-cm capillary break. The soil types encompassed the range of soil textural classes identified in the footprint of the disposal cell. The capillary layer consists of pea gravel. Because the properties of soils within the disposal cell footprint are highly variable, three soil types were tested with three replications of each soil type. The physical and hydraulic properties of these materials have been determined. The sponge-layer thicknesses included a preliminary design thickness (150 cm), based on UNSAT-H modeling (55) and, for comparison, designs with 100- and 200-cm-thick sponge layers.

Table I. Treatment Structure for Small Lysimeter Array

Soil Type	Soil Layer Thickness (cm)	Replications
Clay loam with 30% clay	100	3
Clay loam with 30% clay	150	3
Clay loam with 30% clay	200	3
Loam with 17–24% clay	150	3
Clay with 40–45% clay	150	3
Total		15

The small lysimeter facility consists of five rows of weighing lysimeters with three lysimeters in each row. A 2.1-m-wide trench approximately 16.75-m long was excavated to a depth of 2.2 m. Thirty PVC pipes (38 cm in diameter and 230 cm in length) were placed in the trench using wood bracing to maintain a vertical orientation. These PVC pipes serve as sleeves within which the lysimeters are lowered into and raised out of the ground. As the trench was backfilled, vertical orientation of PVC sleeves was maintained within 0.75 cm from top to bottom. The trench was backfilled to 2.5 cm below the top of the PVC sleeve in 15-cm lifts compacted to achieve 95% standard proctor density. A concrete footing was poured on each side of the length of the lysimeter array to provide a track for a ½-ton gantry.

The lysimeters consist of 30.4-cm (i.d.) PVC pipe fitted with modified PVC end caps. The end caps have an interior PVC ring heat-welded to a sloping bottom plate with two threaded drainage ports, one inside the interior ring and one between the interior ring and the outer wall of the end cap. These double-ring end caps are designed to capture any preferential flow along the inside lysimeter wall separate from drainage through the soil mass. Two lifting ears consisting of three-hole strap gate hinges were bolted flush to the upper outside end of the lysimeter column. Clear, flexible polymer tubes were attached to drainage ports at the lower end of the end cap. Lysimeters were fully assembled, filled with water, and leak tested before they were installed at the site.

Lysimeters were filled by hand using a crane scale, buckets, tampers, steel measuring tapes, and a portable cement mixer. Lysimeters used for water-storage capacity tests were filled from the bottom up in the following sequence: 10 cm of washed gravel, 15 cm of washed sand, a construction-grade geofabric, and either 100-, 150-, or 200-cm of fine soil. The geofabric prevents fines from sifting into the coarse layers during construction. The fine soil layer was placed in 15-cm lifts to simulate construction and to control lift densities. The first lift above the geofabric was wetted and compacted to achieve 95% standard proctor density, which increased water retention at the textural interface. The remaining lifts were placed relatively dry (10 vol.% water) and compacted to obtain a dry-weight bulk density of about 1.4 g/cm^3, simulating the native soil bulk density. In preparation for filling of the lysimeters, bulk soil samples were conditioned in the field using a portable cement mixture, sampled to determine actual moisture content, weighed, and sealed in plastic buckets. Before each lift was placed, the distance from the top of the previous lift to the top of the lysimeter was measured. Prepared soils were weighed and placed in lysimeters, and lifts were compacted with a tamper to achieve prescribed bulk densities. Lysimeters were filled to approximately 2.5 cm below the top. Lift samples were retained for moisture content analysis.(56)

Monitoring Methods

The capped pipes function as combined weighing and drainage lysimeters. Drainage is measured by collecting water from the clear plastic tubes fitted to the drainage ports. Water-storage changes are estimated by suspending lysimeters from a load cell anchored to the gantry. The load cell provided a resolution of approximately 1.4-mm water equivalent. The load cell calibration is checked in the field before and after each sampling session using standard weights. Change in water storage (ΔS), was calculated as

$$\Delta S = (M_t - M_i)/A, \qquad \text{Eq. 1}$$

where M_t is the lysimeter mass (grams) at sampling time t, M_i is the initial lysimeter mass (grams), and A is the cross-sectional area (square centimeters) of the lysimeter. We assumed that changes in lysimeter mass attributable to changes in plant mass were negligible. Initial water storage (S_i, millimeters) for the total lysimeter soil profile thickness (H, millimeters) was calculated from volumetric moisture (θ_i) samples (56) of each lift (L_i) taken during the installation of lysimeters, using the equation

$$S_i = \sum_{i=1}^{n} \theta_i (L_i / H). \qquad \text{Eq. 2}$$

Soil-water balance includes inputs of precipitation (P) and run-on (Ri) and outputs of evapotranspiration (ET), drainage past the plant rooting depths in the soil profile (D), and runoff (Ro). Soil-water storage changes (ΔS) can be expressed as

$$\Delta S = P + Ri - ET - D - Ro. \qquad \text{Eq. 3}$$

Lysimeter soil surfaces were isolated from Ri and Ro, thus ET was estimated using the simplified water balance equation

$$ET = P - D - \Delta S, \qquad \text{Eq. 4}$$

where ET, P, and ΔS were recorded as millimeters of water. Precipitation data are measured with a tipping bucket gauge (Model P501-I, Weather Measurement Corp.) connected to a CR–10 data logger (Campbell Scientific, Logan, Utah).

GJO funded installation of the small lysimeter array in July and August 1993 and then funded monitoring of lysimeters during the 1995 growing season. The Federal Facilities Program of EPA Region 8 and GJO funded resumption of monitoring in 1999. No data were collected from September 1993 through March 1995 or from October 1995 through August 1999.

Lysimeter Array Results and Discussion

Precipitation, water storage, and drainage of all small lysimeters were measured biweekly from April through September 1995 and again monthly from September 1999 to July 2001. Lysimeters were not monitored when covered with snow during winter months. Evapotranspiration was calculated as the mass balance, and water balance data were recorded as millimeters of water.

For all treatments (soil types and layer depths), drainage in the small lysimeters was well below an EPA standard of 3.0 mm/yr (Figure 3).(57) The highest mean drainage over the 7-yr period, 1.56 mm (0.22 mm/yr), was measured in the 200-cm clay loam treatment. Sixty-seven percent of this total (1.05 mm) occurred in a single year, 1995, the first year we measured drainage. Total precipitation in 1995 (442 mm) was only 115% of the 50-yr average (385 mm), but winter and spring precipitation in 1995 was 151% of normal. Drainage levels during the 7-yr period were not significantly different among all other treatments (mean is equal to 0.44 mm or 0.06 mm/yr; $p < 0.05$). The mean drainage for all treatments dropped from 0.29 mm/yr in 1995 to less than 0.01 mm/yr by 1999. Drainage was undetected in all treatments in 2000 and 2001.

The steady decline in drainage during the monitoring period can be attributed to plant root development and increasing evapotranspiration, not to precipitation. Annual precipitation amounts remained above the 50-yr average from 1997 through 2001. The relatively high drainage in the 200-cm clay loam treatment in 1995 may indicate that, unlike the 100-cm and 150-cm treatments, roots had not extended deep enough to extract water at 200 cm and, therefore, moisture content reached saturation at the capillary break. In contrast, we speculate that by the year 2000, roots were deep enough in all treatments that evapotranspiration precluded saturation and drainage across the capillary layer.

Time series of soil-water storage for the 150-cm loam, clay, and clay loam treatments are displayed as millimeters of water in Figure 4. For all treatments, seasonal high and low water storage varied between mid-to-late spring and mid-summer to mid-fall, respectively, depending on the amount and seasonality of precipitation and on the maturity of vegetation. In 1995 and again in 2000, the seasonal low occurred in mid-July and early August; Monticello received close to normal summer (June–September) precipitation both years (124 mm in 1995 and 137 mm in 2000; 50-yr average is 125 mm). In 1999, the seasonal low was delayed until November because of higher than normal summer precipitation (274 mm). For all monitoring periods, mean water-storage values for loam and clay loam were not significantly different ($p < 0.05$).

The highest water-storage levels occurred in 1995 when grasses planted in the lysimeters were still immature. Because we measured drainage for all treatments during the period, we consider these storage values to be roughly equivalent to the drained upper limit (Table II). After the grasses matured

Table II. Drained upper storage limit and water-storage capacity for combinations of soil sponge layer depths and soil type treatments. The drained upper limit is the water storage measurement when drainage occurred in 1995. The water-storage capacity is the difference between the drained upper limit and the lowest measured water-storage level. Means followed by the same letter are not significantly different ($p < 0.05$).

Treatment Layer Depth (cm)	Soil Type	Drained Upper Limit (mm water)	Water-Storage Capacity (mm water)
150	Loam	431 ± 30 c	279 b
150	Clay	493 ± 7 b	170 d
150	Clay loam	449 ± 45 bc	311 b
100	Clay loam	321 ± 3 d	214 c
200	Clay loam	593 ± 30 a	368 a

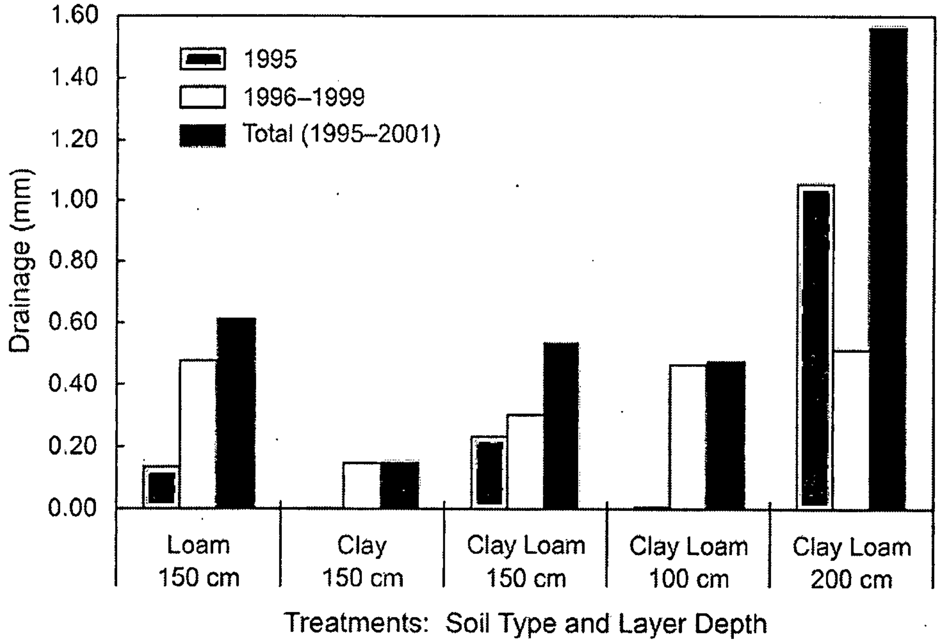

Figure 3. Small lysimeter drainage values for all treatment combinations for 1995, 1996–1999, and the total for 1995–2001. Drainage values for 2000 and 2001 are insignificant and are not displayed.

(1999–2001), peak storage values were from 8% (clay treatment) to 42% (loam and clay loam treatments) below the drained upper limit. Although the drained upper limit was highest for the clay treatment (at 150 cm), the water-storage capacity of the loam and clay loam soil types were between 64% and 83% higher than the water-storage capacity of the clay. These field test results corroborate calculations of net storage based on soil suction head and water content profiles.(54)

COVER PERFORMANCE MONITORING

In 1998 and 1999, GJO teamed with EPA Region 8 on the installation of large drainage lysimeters to evaluate the water balance of the final design for the Monticello disposal cell cover (Figure 5). The cover layer sequence constructed inside the caissons matched as-built engineering parameters for the actual cover. In 2000, GJO and the EPA Alternative Cover Assessment Program (ACAP) collaborated on construction of a large drainage lysimeter to monitor the water balance of a 3-ha facet of the 14-ha disposal cell cover at Monticello. Water-balance monitoring data for both the caisson and large cover lysimeters are accessible on an Internet website managed by the Desert Research Institute for EPA (**http://www.dri.edu/Projects/EPA/acap.html**).

Caisson Lysimeters

Two caisson drainage lysimeters were constructed at Monticello between 1998 and 1999. Construction of the first lysimeter began in fall 1998 to test the Monticello design using local soil materials that we considered best suited for the various cover layers. A second caisson drainage lysimeter was constructed during 1999 using soil materials and matching as-built engineering parameters achieved during construction of the actual disposal cell cover. The two caisson lysimeters provided a side-by-side comparison of the performance of "ideal" and "actual"covers for the Monticello Superfund site.

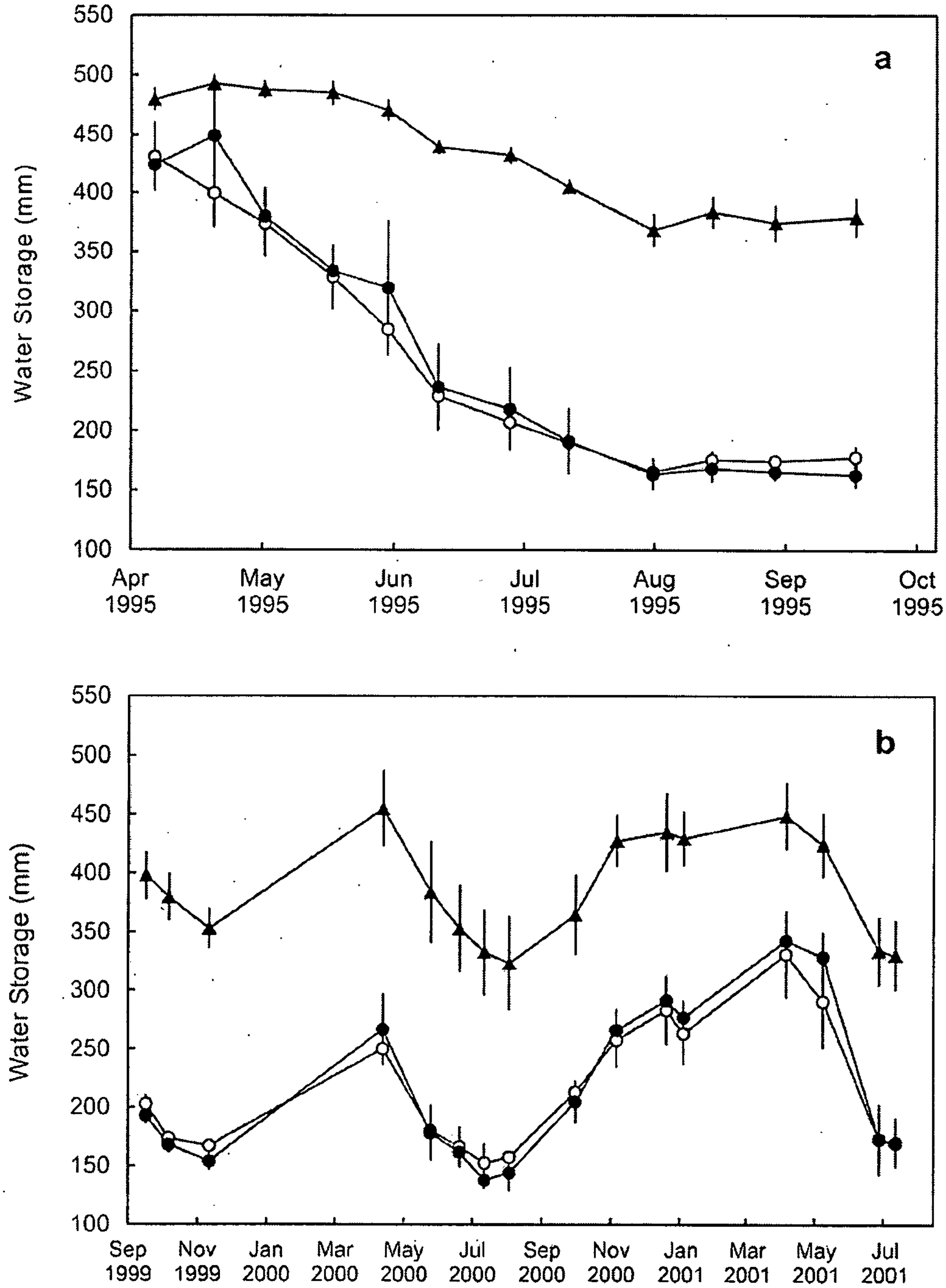

Figure 4. Seasonal water-storage changes for alternative covers with 150-cm soil layers consisting of loam (open circles), clay loam (closed circles), and clay (triangles): (a) during the 1995 growing season and (b) from September 1999 to July 2001. Bars are 2 standard error of the mean; $n = 3$.

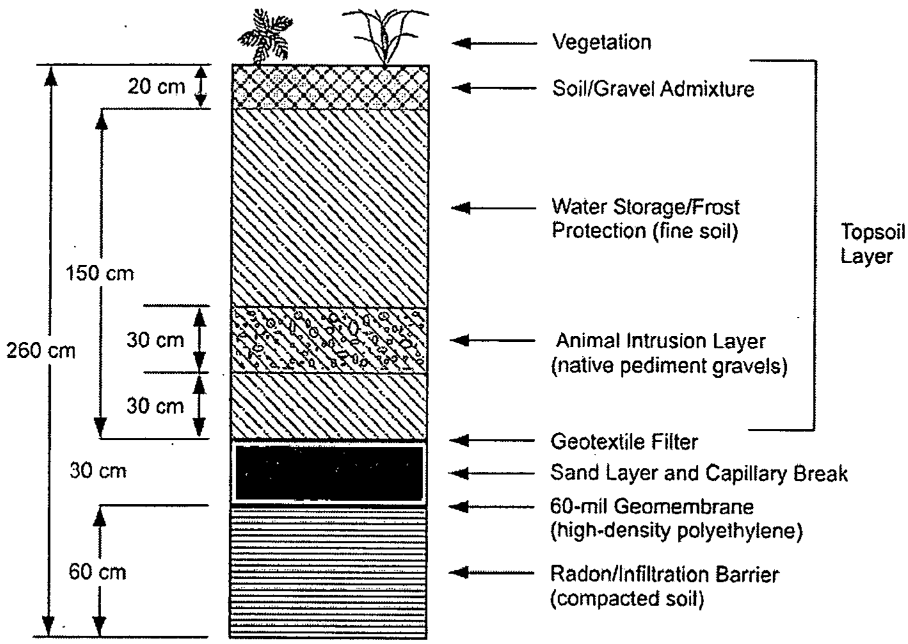

Figure 5. The top-slope cross section of the final cover design for the Monticello, Utah, disposal cell consists of several layers:

- A 60-cm compacted soil layer (CSL) designed for radon attenuation;
- An EPA-required 60-mil geomembrane that serves as a short-term infiltration barrier;
- A 30-cm coarse sand layer that functions as a capillary break and drainage layer;
- A geotextile filter that serves as a layer separator during construction;
- A 170-cm fine-textured topsoil "sponge" layer designed for frost protection and to store precipitation. Rock admixtures are at two depths: a 30-cm cobble layer as a burrowing animal barrier placed 30 cm above the sand layer and a 20-cm gravel admixture at the surface for erosion protection;
- Revegetation with native plants designed to maximize evapotranspiration and remain resilient given environmental fluctuations.

The large caisson lysimeters were constructed of corrugated steel culvert and lined with high-density polyethylene (HDPE). The caissons are 3.05 m in diameter by 2.75 m in depth. Access to the instrumentation is available through an adjacent caisson that is 1.52 m in diameter and 3.66 m in depth. The corrugated steel culverts (lysimeter caisson and instrument access caisson) were bolted together, lowered into a pit using the track hoe bucket, and checked to ensure vertical placement.

The lysimeter culvert was lined with 40-mil HDPE and leak tested. A drainage hole was cut into the lower end of the HDPE geomembrane and welded to an HDPE drainage port. An HDPE flap was welded to the lysimeter wall just above the topsoil lift at a depth of 61 cm below the lip of the lysimeter. The purpose of the flap is to divert any saturated flow moving along the sidewall back into the soil mass. Cover layers were constructed by marking lift and layer heights on the interior wall, shoveling and hauling layer materials to the lysimeter, dumping materials in the lysimeter, spreading and wetting lift materials in the lysimeter, and tamping lifts to achieve bulk density specifications. Instrumentation was installed as the cover layers were constructed. Soil moisture reflectometers (Campbell Scientific, Inc.), thermocouples, and root observations tubes were placed in shallow trenches that had been cut into the soil lifts. Drainage, soil water content, and soil temperature data are monitored hourly, stored in a microprocessor on site, and downloaded periodically using a phone modem.

Cover Lysimeter

During 1999 and 2000, EPA Region 8 and GJO collaborated with ACAP to monitor the performance of a section or facet of the actual disposal cell cover at Monticello. ACAP had been interested in the Monticello disposal-cell cover system since inception of ACAP in 1998. The EPA National Risk Management Laboratory funds ACAP. In October 1999, an agreement was obtained between EPA and DOE on the general design of the study section, and construction was subsequently completed on a 3-ha facet of the existing cover as a test bed to monitor the water-balance component of the cover system.

The primary objective of the cover lysimeter study is to evaluate drainage from a 3-ha collection system that is basically a large-scale water-balance lysimeter. Placement of the plastic geomembrane beneath the test cover soils (Figure 5) created the large-scale lysimeter. A flap of HDPE material was heat-welded to a section of the as-built cover system in October 1999. The flap was designed to capture any lateral or vertical drainage from the 3-ha facet. A pipe was welded into the most downgradient edge of the flap, thus capturing all drainage from this study section. Collected water is conveyed through a boot in the geomembrane to a redundant measurement system of three devices located in a water-collection basin (vault) positioned hydraulically downgradient from the collection area. A datalogger records the measurements taken by all three devices hourly. Volume of drainage is measured first by a tipping bucket and then by a dosing siphon. A pressure transducer located at the bottom of the dosing siphon vault is also able to assess drainage from the test section by measuring the elevation (or stage) of the water in the vault before the dosing siphon empties the water.

Several measurements were made to define the soil hydrologic conditions and monitor the climatology and plant community at the site. Direct measurement of four parameters for the water-balance equation (precipitation, drainage, runoff, and change in water storage) is possible. Actual ET (AET) is estimated by difference. Potential ET (pET) is estimated by calculation of the energy budget (Penman-Montieth equation) (58) using the field parameters of wind speed, relative humidity, solar radiation, and air temperature. Engineering and hydrologic characterization of the soils is complete. Climate data, as well as changes in soil moisture status, will be collected for the duration of the study. Data collection for plant community composition, abundance, leaf area, and seasonality of growth began in 2001 and will continue for 5 yr. Climate conditions (wind speed and direction, air temperature, solar radiation, relative humidity, and precipitation) are monitored by a weather station installed at the site. Precipitation is measured by a tipping-bucket rain gauge outfitted with a snowfall adapter. In addition, surface runoff is diverted by wood boards around a 10-m by 20-m area, collected at the low end of the plot, and diverted to a water-collection basin similar to that used for drainage.

Moisture content of the soils is measured using water content reflectometers (Campbell Scientific, Inc.). The reflectometers measure the effective dielectric as a pulse transit time, which in turn is calibrated against water content. Changes in soil moisture will be determined by reading the water-content reflectometer probes hourly. Soil suction (moisture potential) is determined with heat dissipation units. Sensors in the heat dissipation units consist of a heat source and a heat sensor contained within a porous ceramic housing (Campbell Scientific, Inc.). The heat sensor (thermocouple) monitors the dissipation of a heat pulse generated by a resistive heater element. Heat dissipation is a function of the water content of the ceramic housing that is assumed to be in equilibrium with the suction or matric potential of the surrounding soil. Soil temperature is measured by the heat-dissipation unit sensors. A combination of laboratory measurements was used to evaluate the hydrologic and engineering properties of the cover soils. Samples were collected during the construction of the study section for determination of grain size, Atterberg limits, moisture-density relationships for cohesive soils, minimum and maximum density for cohesionless soils, saturated hydraulic conductivity, specific gravity, and soil moisture-retention relations.

CONCLUSIONS

Results of small weighing lysimeter studies installed at the Monticello, Utah, Superfund site supported construction of a disposal cell cover that relies in part on storage of precipitation in a thick, fine-textured soil layer for seasonal removal by ET. Lysimetry is the most direct and reliable method for evaluating the soil-water balance of disposal cell cover designs. We first evaluated the reliability of small inexpensive lysimeters by testing the hypothesis that plant water relations inside small lysimeters and in adjacent undisturbed areas are the same. These initial small lysimeters contained intact soil monoliths overlying capillary barriers and supporting mature native grasses. Plant-water relations data indicate that plants were seasonally more stressed inside the lysimeters than in the adjacent plant community, suggesting that small lysimeters would moderately underestimate ET. For screening tests consisting of multiple treatments and replications, we concluded that the small lysimeters would provide reasonable comparisons of the hydrologic performance of ET-type cover designs.

The monolith lysimeter results supported our decision to install an array of 15 small weighing lysimeters to screen different ET and capillary barrier designs constructed with a range of soil layer thicknesses (100, 150, and 200 cm) and local soil types (loam, clay loam, and clay). Although all designs performed adequately and drainage was well below a 3.0-mm standard for all treatments, 150-cm loam and clay loam designs had equal and the best performance records. The 200-cm clay loam design had the highest water-storage capacity but also the highest drainage, possibly because early in the study rooting depths of the immature grasses did not provide adequate water extraction, causing saturation at the capillary break. The 150-cm clay design had a high field capacity (drained upper limit) but the lowest water-storage capacity of all treatments; the clay retained too much water. We are currently using large caisson lysimeters and in situ instrumentation to monitor the hydrologic performance of the completed disposal cell cover at Monticello.

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